Final Technical Report:

Radar Interferometric Studies of Jetstream Vertical Velocities and Precipitating Regions.

AFOSR Grant # AFOSR-94-1-0440

P.I.: M. F. Larsen
Dept. of Physics
Clemson University
Clemson, SC 29634
Tel. 864-656-5309
E-mail: mlarsen@clemson.edu

May 31, 2000

REPORT DOCUMENTATION PAGE

AFRL-SR-BL-TR-00-

0345

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. R...
	May 31, 2000	Final Technical Report 1 Sep 94 to 31 Aug 98

4. TITLE AND SUBTITLE
Radar Interferometric Studies of Jetstream Vertical Velocities and Precipitating Regions

5. FUNDING NUMBERS
F49620-94-1-0440

6. AUTHOR(S)
Dr. M. F. Larsen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Clemson University
Physics Department
204 Kinard Lab
Clemson, SC 29634-1911

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NM
801 N. Randolph St, Rm 732
Arlington, VA 22203-1977

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-94-1-0440

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The research project involved studies of the vertical circulation within frontal zones and near jet-streams using interferometric radar techniques. Application of interferometric techniques to deter-mine the angle of arrival of the signal within the finite radar beam width has shown that nominal vertical beam measurements often have significant biases due to inclined aspect sensitive struc-tures, especially in the vicinity of fronts and near jetstreams. The intefferometric technique makes it possible to apply corrections to the raw Doppler velocities which were then Used to calculate the two-dimensional spectra of the velocity fluctuations as a function of the vertical wavenumber and frequency. The spectra that were calculated show two breaks. One is at the linear instability threshold determined by the wave breaking criterion. The other is at the boundary determined by the diffusive limit. In addition, the Scorer parameter which determines the vertical wavenumber cut-off for vertically-propagating orographic waves was found to be important in determining the character of the wave spectrum.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	14
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Summary

The research project involved studies of the vertical circulation within frontal zones and near jetstreams using interferometric radar techniques. Application of interferometric techniques to determine the angle of arrival of the signal within the finite radar beam width has shown that nominal vertical beam measurements often have significant biases due to inclined aspect sensitive structures, especially in the vicinity of fronts and near jetstreams. The interferometric technique makes it possible to apply corrections to the raw Doppler velocities which were then used to calculate the two-dimensional spectra of the velocity fluctuations as a function of the vertical wavenumber and frequency. The spectra that were calculated show two breaks. One is at the linear instability threshold determined by the wave breaking criterion. The other is at the boundary determined by the diffusive limit. In addition, the Scorer parameter which determines the vertical wavenumber cut-off for vertically-propagating orographic waves was found to be important in determining the character of the wave spectrum.

Contents

1 Introduction

The objective of the research project was to study the the vertical circulation in the vicinity of the jetstream and in precipitating regions using *UHF* Doppler radar measurements and *VHF* interferometric radar measurements. Observations were made with the *UHF* radar facility located in Søndre Strømfjord, Greenland, and the *VHF* radar located in Shigaraki, Japan, near Kyoto University. Our data analysis has shown

- that the refractive index surfaces are inclined by a few tenths of a degree in typical midlatitude flow conditions,
- that the direction in which the layer is inclined correlates well with the wind direction, and
- that the vertical velocity measurement error introduced by the layer inclinations is comparable in magnitude to the typical vertical velocities, i.e., 10–20 cm s^{-1}.

We have also shown that effective off-vertical in-beam incidence angles can result from divergence in the flow even if the reflectivities are uniform within the region illuminated by the radar beam. The latter result suggests that biases can be introduced in vertical beam Doppler measurements even if the wavelength is short and the scatter is not aspect sensitive.

The data obtained with the two radars has shown

- that the shape of the two-dimensional power spectrum of the velocity fluctuations in the vertical wavenumber/frequency domain is controlled both by diffusive damping and by wave breaking instabilities,
- that the upward vertical fluxes of wave momentum are strongly controlled by the background flow with the largest fluxes occurring in connection with frontal passages,
- that the detailed vertical structure is strongly related to the Scorer parameter which determines the cut-off vertical wavelength for vertically-propagating orographic waves, and
- that strong turbulence is found at altitudes in the stratosphere where critical levels for orographic waves occur.

During the last year of the project an effort was made to develop a new balloon system to make it possible to measure the temperature, pressure, and winds with three or more balloons simultaneously in order to determine the horizontal gradients in the refractive index structures and the winds. The balloon payloads were completed and tests were carried out at Clemson.

The next section lists the personnel involved in the project. The following section describes the research results in more detail.

2 Personnel

In addition to the P.I., three graduate students at Clemson University were involved in the research related to the project. They were Mr. Willis Chang, Mr. Grant Williams, and Mr. Chris Odom.

Mr. Chang received his Ph.D. in December 1995, and the results of his research were published in his dissertation entitled "Application of MST radar wind estimation techniques to the study of gravity waves in the lower stratosphere and troposphere."

Mr. Williams completed his Masters degree in December 1996. His research involved work with the radar in Greenland and the design of an interferometric radar system which had applications both for meteor studies and the lower atmosphere interferometric studies. The results were published in the thesis entitled "Design and implementation of a *VHF* meteor radar."

Mr. Odom worked with the radar in Japan but took an extended leave of absence from the graduate program before completing the Ph.D. He is scheduled to return to Clemson in June 2000.

3 Summary of Research Results

The primary sources of data for the analysis carried out during the research project were the NSF radar located at Søndre Strømfjord, Greenland, and the Kyoto University radar located at Shigaraki, Japan. Both have unique capabilities for probing tropospheric and lower stratospheric winds, waves, and turbulence structure, including large transmitter power with peak power in the megawatt range and large-aperture antennas that can provide vertical resolution of 100's of meters and temporal resolution of a few minutes.

3.1 Greenland experiments

The large 1290-MHz radar operated by NSF at Søndre Strømfjord, Greenland, is capable of routinely observing winds and turbulence in the height range between approximately 6 and 21-km altitude, i.e., encompassing the jetstream altitudes. The lower altitude is limited by the somewhat slow transmit/receive switch that is part of the system.

An example of the reflectivities measured with the radar during a ten-hour period on January 20–21, 1992, is shown in Figure 1. The layer of enhanced reflectivities near 10 km is associated with a layer of cirrus located immediately above the jetstream altitude. Additional layers are evident between 15 and 20-km altitude. At higher altitudes near 25 km, an isolated layer is evident that lasts for approximately 5 hours during the early part of the observation. The corresponding vertical velocities are shown in Figure 2. The layers between 15 and 20-km altitude have predominantly upward vertical velocities associated with them, and that is also the case for the isolated layer near 25 km.

The temperature and background wind profile for the first part of the observation period is shown in Figure 3 which represents the radiosonde data from 2300 UT at Egedsminde located near the *UHF* radar. Comparing the temperature profile and the reflectivity measurements indicates that the layers in the altitude range between 15 and 20 km occur in the region where the temperature profile becomes more stable. As the stability increases, the vertical wavelength becomes shorter and conditions are more conducive to wave breaking. The layer near 25 km is located at an altitude where both the zonal and meridional wind components approach zero. That altitude is a critical level for orographic waves and should be a region of increased instability for waves approaching that level. The radar measurements are typically limited to altitudes below 21 or 22 km, so having relatively large reflectivities at 25 km is unusual, but the data show the important role of gravity wave instabilities in accounting for the reflectivity, and thus the refractivity structure, above the tropopause height.

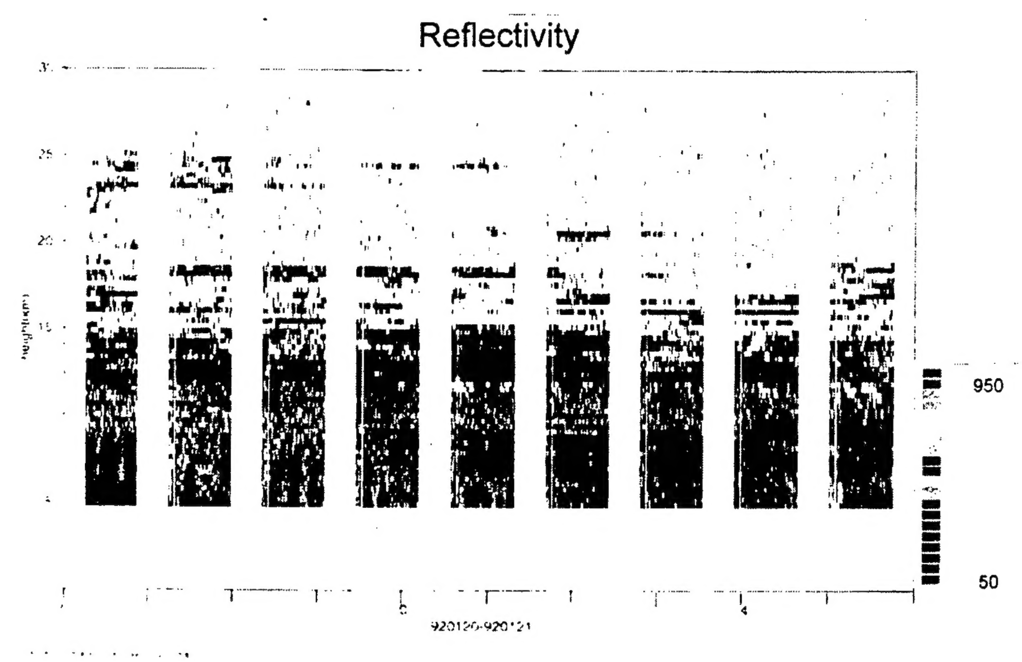

Figure 1:

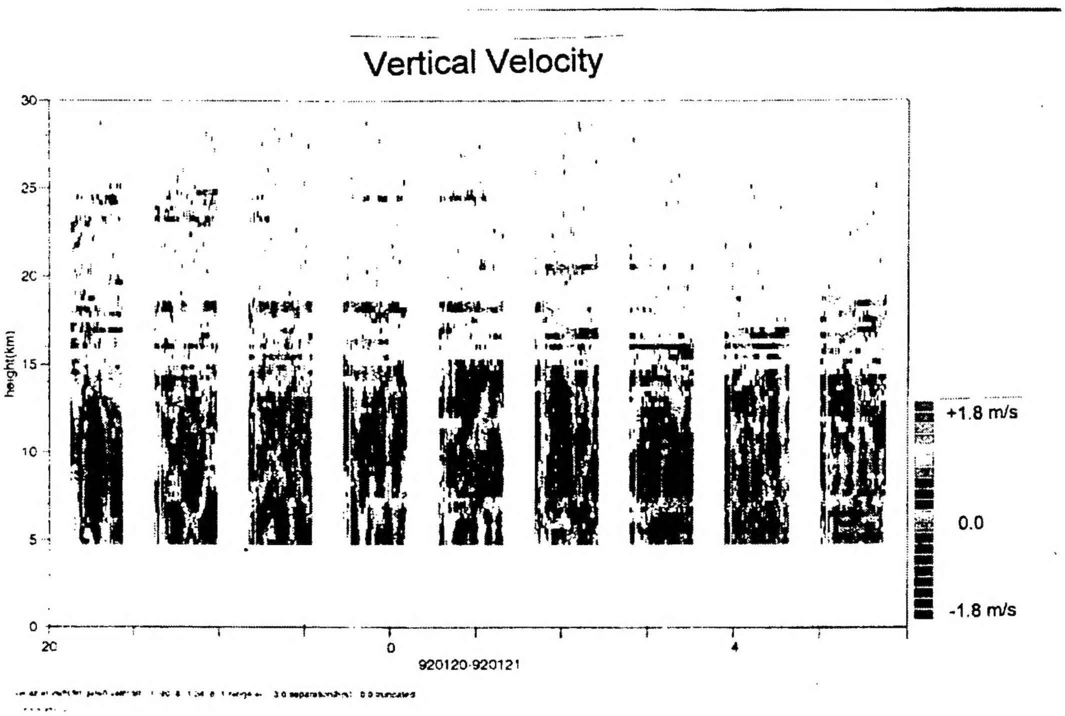

Figure 2:

3.2 Japan experiments

The MU radar is located at Shigaraki, Japan, near Kyoto, and operates at a frequency of 53.5-MHz. The phased array antenna diameter is 104 m. The system transmitters are capable of producing up to 1 kW peak power. Beam directions can be switched from pulse to pulse so that near-simultaneous multiple beam direction measurements can be obtained. Since the antenna array can be split into as many as 4 separate segments for reception, interferometric measurements are also possible. The unique capabilities of the MU radar, as well as the flexibility of the receiving antenna configurations, make it an ideal system for studying radar wind estimation techniques and midlatitude dynamics. In-depth analyses of several data sets obtained with the MU radar were carried out in the course of the study, and the results are described in the dissertation by *Chang* [1995]. Highlights will be described below.

3.2.1 Aspect sensitivity and in-beam incidence angle effects

By splitting the receiving antenna into four parts and receiving on each simultaneously, the arrival angle of the dominant scatter within the vertical beam can be estimated by combining the phase

Egedesminde Rawinsonde
920120 2300 UT

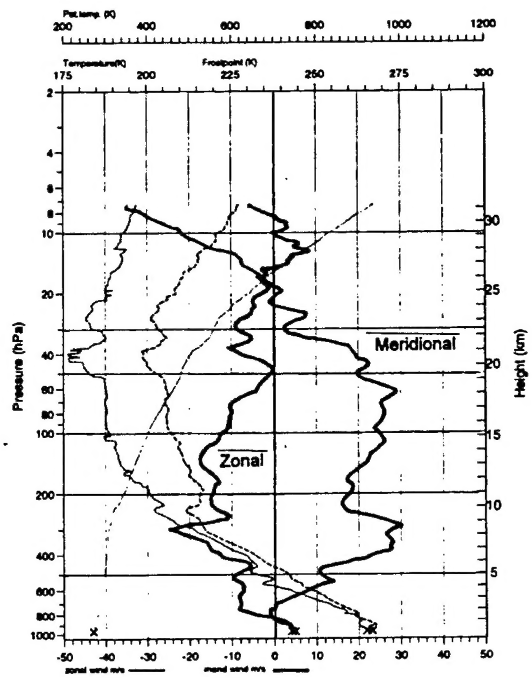

Figure 3:

information in the various receivers. The results for the analysis of several days of data are shown in Figures 4–6. Figure 4 shows the average incidence angle as a function of altitude. The angles are generally 0.2° or less, but even such small angles are sufficient to produce components of the much larger horizontal winds along the effective beam direction that are comparable to the vertical velocities. Figure 5 shows both the vertical velocity estimated directly from the Doppler shift in the vertical beam data (solid lines) and the vertical velocity corrected for the small off-vertical incidence angle (circles). The corrections, especially in the upper troposphere between 6 and 13 km, are comparable in magnitude to the vertical velocities obtained without any correction. Indeed, in the lower part of the height range, the corrected velocities are actually larger than the velocities estimated without corrections, showing that simple vertical beam Doppler measurements of the vertical velocities will tend to underestimate the strength of the vertical circulation.

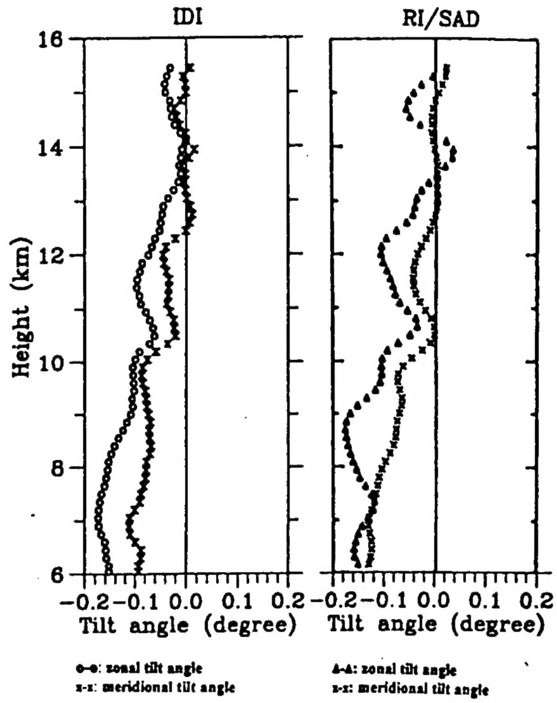

Figure 4:

The interferometric radar data can be used to estimate both the zenith angle of the dominant scatter and also the azimuth angle. Figure 6 shows the average azimuth angle for the incident scatter (circles) compared to the wind direction azimuths (solid line) over the same altitude range. There is clearly a strong correlation between the two, indicating that the refractive index surfaces are inclined in the direction of the mean wind. Such a direct relationship between the two azimuth angles is surprising in general but especially since it exists over nearly all of the altitude range that was sampled in both the troposphere and lower stratosphere, i.e., both in regions with strong aspect sensitivity and without. In order to determine if an effective off-vertical incidence angle can be produced in flow without strong aspect sensitivity, we considered an illuminated region with uniform reflectivity and in-beam flow gradients [*Larsen and Palmer*, 1996]. The analysis showed that the weighting produced by the distribution of velocities when the flow is divergent leads to dominant scatter at a point in the spectrum that corresponds to an off-vertical incidence angle. Effective off-vertical incidence angles can therefore result from divergence alone, even if the scatter is isotropic or the refractive index surfaces are horizontal. Since the effect is related to the divergence, we expect a displacement of the off-vertical incidence angle in the direction of the

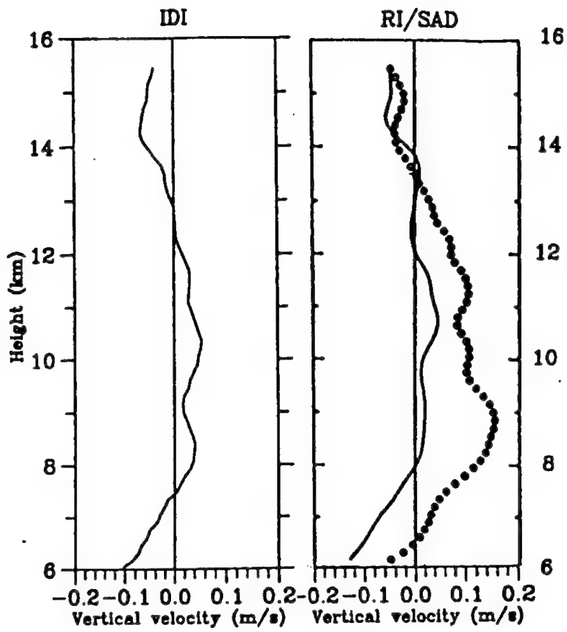

Figure 5:

wind, similar to the result shown in Figure 6.

3.2.2 Two-dimensional gravity wave spectra

One-dimensional gravity wave spectra have been observed extensively by various investigators in the past using MST radars. In our studies, we were able to analyze the spectra for both the corrected and uncorrected vertical velocities. The results show that the spectra for the uncorrected velocities are generally less steep than those for the corrected velocities [*Chang*, 1995]. The differences are large enough that such corrections need to be taken into account when interpreting the dynamical processes responsible for the spectral shapes.

Since the MU radar provides data with both good time and height resolution, we were also able to apply two-dimensional spectral analysis to an extended series of tropospheric and lower stratospheric wind measurements made with the MU radar over a ten-day period. An example of the results is shown in Figure 7.

The analysis shows a change in the spectrum at both the linear cut-off due to wave breaking instability and the nonlinear cut-off due to diffusive filtering. The region affected by the nonlinear cutoff is, for the most part, outside the range associated with vertically-propagating waves. The linear cut-off, however, is very much within the range of interest. These results are described in

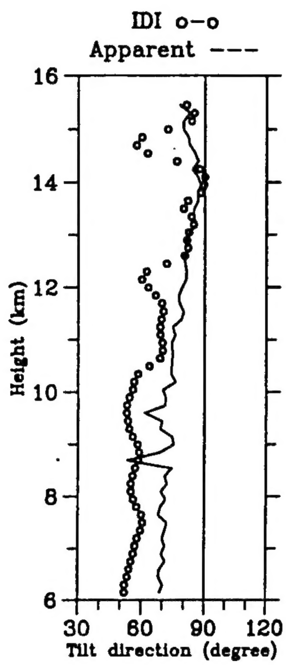

Figure 6:

more detail in the article by *Chang et al.* [1996].

The nonlinear wave filtering effects are created by eddy diffusive processes associated with a broad range of spectral components, i.e., all components with wavelengths shorter than the wavelength of interest. The linear instability theory is linear in the sense that the wave components are treated individually, and the linear formulation is used to describe the wave growth up to the point where breaking occurs.

Our results suggest that the two processes are distinct and that they both apply, although the linear instability theory appears to be more relevant to the problem of describing the processes that lead to wave breaking. The theoretical work has generally proposed the two dynamical formulations as alternative explanations of the same phenomenon rather than as competing processes. Based on the characteristics of the two-dimensional spectra, a parameterization based on the linear instability theory appears to be most promising for a description of the effects of wave drag on the tropospheric circulation.

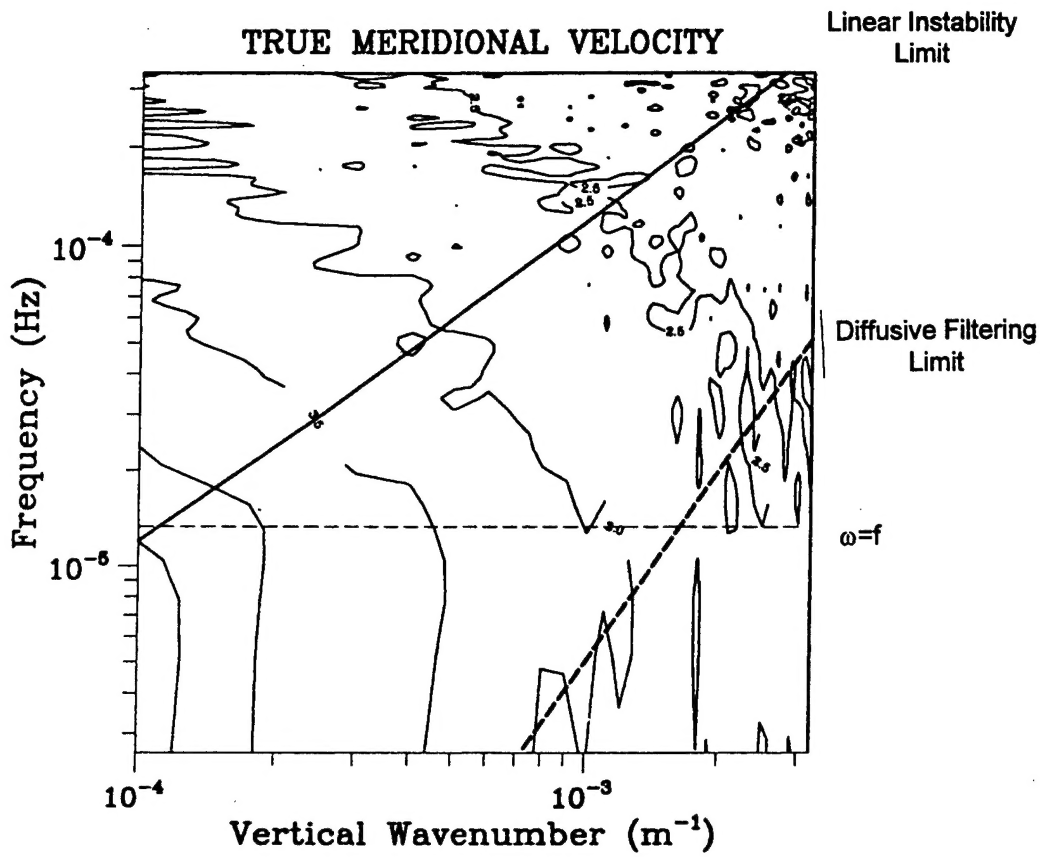

Figure 7:

3.2.3 Momentum fluxes

Measurements along multiple beam directions make it possible to obtain estimates of the vertical momentum flux as a function of time and height. The MU radar is especially well-suited to such measurements since the pulse-to-pulse beam switching make it possible to sample all the beam directions nearly simultaneously. Another possibility is to use an interferometric technique such as the modified imaging Doppler interferometry technique since that allows us to obtain corrected vertical velocity estimates, i.e., corrected for in-beam incidence angle effects.

We have used multiple-beam direction measurements to obtain the vertical momentum fluxes during periods when frontal zones and jetstreams passed the radar site. Furthermore, by calculating

the change in the momentum flux with height, we were able to estimate the acceleration induced in the mean flow by wave breaking effects.

The results showed that the wave-induced accelerations were small during the period prior to a frontal passage, but the acceleration became negative in the vicinity of the altitude of the jetstream during the jetstream/frontal passage. The negative acceleration indicates that wave breaking is decelerating the flow at the upper levels.

The analysis also showed that the character of the spectrum of upward-propagating waves was strongly influenced by the Scorer parameter calculated from the temperature and wind profiles obtained from radiosonde stations located near the MU radar. The Scorer parameter is an estimate of the vertical wavelength cut-off for vertically-propagating orographic waves. Our analysis showed that the wave energy and vertical momentum fluxes decreased as the cut-off wavelength decreased. These results are described in detail in the dissertation by *Chang* [1995].

3.3 Simultaneous multi-balloon technique

The radars and other remote sensing techniques provide a wealth of information about the vertical structure and temporal evolution of the flow, but horizontal gradients are still difficult to measure. In situ balloon measurements are still an excellent source of information about the temperature and humidity structure in the troposphere and stratosphere, but they have two drawbacks. One is that the commercial systems are generally expensive, and the other is that the capability to make simultaneous measurements with multiple balloons requires special adaptations of the standard systems.

In the course of the research we worked in collaboration with the University of Nebraska to develop and test a low cost balloon system which would provide pressure, temperature, and humidity measurements through telemetry to the ground, and wind measurements by photographic tracking. The systems were also designed to operate at offset frequencies so that the information from multiple balloons could be received simultaneously with a broadband receiver and decoded later to separate the signals from the individual balloons. The system was tested at Clemson after the development was completed and the results are described in the article by *Corner et al.* [1999].

4 Publications

Chang, Y., *Application of MST Radar Wind Estimation Techniques to the Study of Gravity Waves in the Lower Stratosphere and Troposphere*, Ph.D. Dissertation, Clemson University, Clemson, South Carolina, 118 pp., December 1995.

Chang, Y., M. F. Larsen, R. D. Palmer, M. Yamamoto, S. Fukao, and T. Tsuda, A study of two-dimensional gravity wave spectra in the troposphere and lower stratosphere, *Solar-*

Terrestrial Energy Program, SCOSTEP Secretariat, NOAA, Boulder, Colorado, 438–440, July 1996.

Corner, B. R., R. D. Palmer, and M. F. Larsen, A new radiosonde system for profiling the lower troposphere, *J. Atmos. Ocean. Tech.*, *16*, 828–836, 1999.

Larsen, M. F., and R. D. Palmer, A relationship between horizontal flow divergence and in-beam incidence angles, *Solar-Terrestrial Energy Program*, SCOSTEP Secretariat, NOAA, Boulder, Colorado, 441–444, July 1996.

Williams, G. G., *Design and Implementation of a VHF Meteor Radar*, Masters Thesis, Clemson University, Clemson, South Carolina, 53 pp., December 1996.